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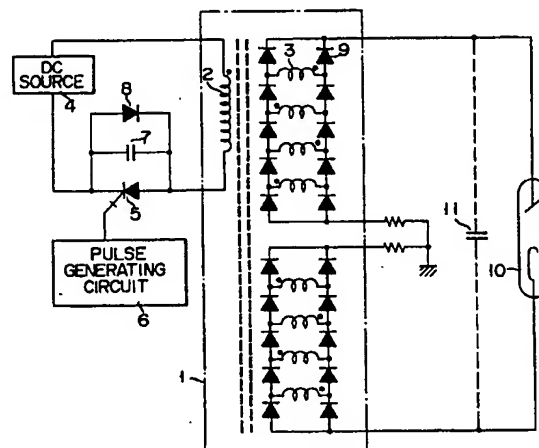
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High voltage generator.

A high voltage generator comprises a voltage resonance switching circuit which consists of a transformer (1), a GTO thyristor switching element (5) connected between the primary winding (2) of the transformer (1) and a D.C. source (4), and a voltage resonance capacitor (7) connected in parallel to the switching element (5). The transformer (1) is the coreless type. A rectifier circuit (9) is connected to the secondary winding (3) of the transformer (1) to rectify an output current from the rectifier circuit (9).



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High voltage generator

This invention relates to a power source for supplying high voltage to a load and, more particularly, to a high voltage generator adapted as a power source for an X-ray tube, etc.

5 An X-ray tube is generally operated by high voltage ordinarily ranging between 100 and 400 KV, with a larger power consumption than 100 KW. With a conventional high voltage generator for supplying high voltage to a load such as an X-ray tube, the common process of providing
10 high voltage has been to step up a commercial power source by means of a transformer whose core is constructed by laminating silicon steel plates. Procurement of high voltage and high power from a commercial power source operated at a low frequency
15 requires an extremely large transformer, making it necessary to provide a large high voltage generator.

To cope with the above-mentioned difficulties, studies have been conducted in recent years to miniaturize a transformer and reduce the capacity
20 of a power source for a high voltage generator by applying a converter having as high a switching frequency as several hundred Hz for power conversion. In the above-mentioned power conversion, a large power of, for example, 1,000 amperes is generally
25 switched. Therefore, a high speed gate turn-off (GTO) thyristor, applied as a switching element,

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can have its operation frequency only raised to a level of about 1 KHz, if switching loss is taken into account. Consequently, a limitation is imposed on the miniaturization of the transformer, thereby unavoidably
5 resulting in the enlargement of the high voltage generator. In the above-mentioned large power conversion, difficulties arise in elevating the operation frequency of a switching element in view of the switching loss which may take place. Consequently,
10 the miniaturization of the transformer has been considered unrealizable, if the power transmission efficiency of the transformer is taken into account.

Since the core undergoes magnetic saturation, a limit is imposed on the magnetic flux density B
15 (magnetic saturation is reached at about 0,8T (8,000G) in the case of a silicon steel plate and at about 0,3T (3,000G) in the case of a ferrite plate). For the transmission of high power, the cross sectional area of the core has to be enlarged. The above-mentioned
20 magnetic saturation has also been regarded as one of the causes which obstructs the miniaturization of the transformer.

As seen from the foregoing description, the application of a large transformer results in the
25 enlargement of the whole high voltage generator, thus requiring, a great deal of work and time in the transportation and installation of a large high voltage generator. Moreover, such a large high voltage generator imposes further limitations on the selection
30 of a site for its installation.

It is accordingly the object of this invention to provide a high voltage generator which ensures the miniaturization of a transformer by applying a high operation frequency and the efficient conversion of
35 high voltage and high power.

To attain the above-mentioned object, this invention provides a high voltage generator, wherein

a switching element is connected between a D.C. source and the primary winding of a coreless transformer. A voltage resonance type switching circuit is provided by connecting a voltage resonance capacitor in parallel
5 to the switching element or the primary winding of said coreless transforms. A rectifier circuit for rectifying an output current is connected to a secondary winding of said coreless transformer.

The high voltage generator of this invention
10 offers the advantages that the efficient conversion of a large power can be effected by utilizing voltage resonance with a higher frequency than, for example, 1 KHz, and the application of the aforementioned coreless transformer and high frequency operation
15 realize the miniaturization of the transformer and, consequently, the miniaturization of the whole high voltage generator and its efficient operation.

This invention can be more fully understood from the following detailed description when taken in conjunction with the accompanying drawings, in which:
20

Fig. 1 is a circuit diagram of a high voltage generator according to a first embodiment of this invention;

Fig. 2 is a theoretic equivalent circuit diagram
25 of Fig. 1;

Figs. 3A to 3C are schematic equivalent circuit diagrams representing the respective operation stages of the high voltage generator of Fig. 1;

Fig. 4 indicates signal waves appearing in the
30 various sections of the high voltage generator of Fig. 1;

Fig. 5 sets forth the relationship between the operating frequency and the quantity of supplied power, in case a plurality of high voltage generators are
35 formed with substantially the same construction as that of Fig. 1, by applying a transformer having a different inductance each time;

Fig. 6 is a circuit diagram of a high voltage generator according to a second embodiment of the invention; and

5 Fig. 7 is a circuit diagram of a high voltage generator according to a third embodiment of the invention.

A description may now be made with reference to Fig. 1 of a high voltage generator according to a first embodiment of this invention. The transformer 1
10 comprises a primary winding 2 and a plurality of independent secondary windings 3 and is rendered coreless (namely, has an air core). A D.C. source 4 is formed of a rectifying power source for rectifying and smoothing, for example, a commercial power source.
15 Connected between a pair of output terminals of said D.C. source 4 is a series circuit consisting of the primary winding 2 of the transformer 1 and GTO thyristor 5 acting as a switching element. The gate of the GTO thyristor 5 is supplied with an output control pulse from
20 a control pulse generator 6. The GTO thyristor 5 is opened and closed in response to said control pulse with a prescribed frequency of, for example, 10 KHz and a specified interval. A voltage resonance capacitor 7 is connected in parallel to the anode and cathode of
25 the GTO thyristor 5. A dumper diode 8 is connected in inverse parallel to the anode and cathode of the GTO thyristor 5. The foregoing description represents a voltage resonance switching circuit in which the primary winding 2 of the transformer 1 is used as a
30 load.

Provided on the secondary side of the transformer 1 are a plurality of groups of rectifier diodes 9 connected in series in the same polar direction. A plurality of secondary windings 3 are respectively
35 connected between a junction of every two adjacent diodes constituting one group and a junction of every two corresponding adjacent diodes constituting

another adjacent group. In this case, each secondary winding has a polarity opposite to that of the adjacent secondary winding, as indicated by a dot "." attached to the respective secondary windings. Thus, all the rectifier diodes and secondary windings jointly constitute a ladder-shaped circuit. The rectifier diodes collectively constitute a rectification circuit which eventually adds up all the output currents from the plural secondary windings in the direction of the same polarity and performs full-wave rectification. An X-ray tube 10 is connected to said rectification circuit as a high voltage and high power load. The capacitor 11 shown in Fig. 1 represents a stray capacitive component remaining in a cable through which power is supplied from the transformer 1 to the X-ray tube 10, and acts as a smoothing capacitor for high frequency power.

Referring to the equivalent circuit of Fig. 2 corresponding to the high voltage generating circuit of Fig. 1, the coreless transformer 1 is equivalently constituted by an ideal transformer 12, exciting inductance 13, and leakage inductance 14 prevailing between the primary winding 2 and secondary winding 3.

Now let it be assumed in the above-mentioned arrangement of the subject high voltage generator that the GTO thyristor 5 is operated by a control pulse having such a wave as shown in Fig. 4; the GTO thyristor 5 is opened and closed for a prescribed period T , in which the thyristor 5 is rendered conducting for a specified period T_{on} , showing the stabilized circuit condition of the subject high voltage generator; the GTO thyristor 5 acts as an ideal switch which indicates no resistance when rendered conducting, and presents an infinite resistance when rendered nonconducting; and the condition of voltage resonance is mainly defined by the voltage resonance capacitance 7 and leakage

inductance 14. A description may now be made of the operation of the subject high voltage generator on the basis of the above-mentioned assumption. As seen from the waveform of the control pulse shown in Fig. 4, the GTO thyristor 5 fails to retain a state of saturated conduction, unless a gate current always runs through said GTO thyristor 5, and indicates a slight time lag (a storage period T_s) between the point of time at which a reverse bias nonconducting pulse is issued and the point of time at which the GTO thyristor 5 is rendered nonconductive. As used herein, the leakage inductance 14 is defined to mean an inductance as viewed from the primary side of the transformer 1 when the secondary winding 3 thereof is short-circuited.

When the GTO thyristor 5 is rendered conductive for a period T_{on} (t_0 to t_1), then the resultant equivalent circuit presents such an arrangement as shown in Fig. 3A. The exciting inductance 13 of the transformer 1 appears between both output terminals of the D.C. source 4. At this time, the ideal transformer 12 is connected to the prescribed one of the two output terminals of the D.C. source 4. Now let it be assumed that L_p represents the value of the exciting inductance 13; L_e denotes the value of the leakage inductance 14; E_{in} shows the voltage of the D.C. source 4; and E_{out} indicates the average voltage of a power supplied to the X-ray tube 10. Then, the current i_c running through the GTO thyristor 5 during the above-mentioned period may be expressed as follows:

$$i_c(t) = \frac{E_{in}}{L_p} t + \frac{E_{in} - nE_{out}}{L_e} \cdot t ,$$

where n sets forth the ratio which the number of turns of the primary winding of the transformer 1 bears to those of the secondary winding thereof, namely, the transformation ratio of the ideal transformer 12 of

Fig. 2. During the aforementioned period, the current i_c conducted through the GTO thyristor 5 linearly increases as indicated by the current waveform of Fig. 4.

5 During the subsequent period (t_1 to t_2) which extends between the point of time at which the GTO thyristor 5 is rendered nonconductive and the point of time at which the diode 8 is rendered conducting, the equivalent circuit shows the arrangement of
10 Fig. 3B. Thus, the current flowing through the exciting inductance 13 and the current conducted through the leakage inductance 14, that is, an inertial current, are brought into the capacitor 7 for its charge. Consequently, the terminal voltage
15 of the capacitor 7, namely, a voltage V_C impressed across both terminals of the GTO thyristor 5 increases, while delineating a resonance as shown in Fig. 4. The voltage reaches a maximum level defined by the condition of resonance and later drops. The terminal
20 voltage of the capacitor 7 tends to have a negative value, indicated by a broken line in Fig. 4, by the action of resonance after the terminal voltage V_C again falls to zero at point of time t_2 . At this time, however, the diode 8 is rendered conductive
25 by the forward bias. Therefore, during the period T_d (t_2 to t_3) which lapses before the GTO thyristor 5 is again rendered conductive, the terminal voltage V_C is retained at zero. An equivalent circuit during the above-mentioned period presents the arrangement
30 of Fig. 3C. The inertial current i_l passing through the exciting inductance 13 retains a limited negative value as shown in Fig. 4, even when the terminal voltage V_C of the capacitor 7 falls to zero, and flows to the D.C. source through the diode 8. The
35 circuit of a high voltage generator embodying this invention is designed in such a manner that, as shown in Fig. 4, the inertial current i_l delineates

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a waveform representing its running course by which said inertial current i_L first falls to the negative side as mentioned above, and then regains a zero level at the termination of a switching period T , namely, in the proximity of the starting point of the succeeding switching period (when the switching element 5 is rendered conductive a second time). To realize the above-mentioned circuit arrangement, it is fundamentally advised to prescribe the constants of the various circuits. The high voltage generator of this invention not only involves said advised consideration but also carries out a self-stabilizing function. Therefore, same displacement of timing, from the point of time at which the inertial current i_L regains a zero level, is automatically corrected by the circuit itself, which therefore tends to be stabilized, as shown in Fig. 4.

A description may now be made of the magnitude of the power which the subject high voltage generator supplies to the load 10. As seen from Fig. 4, the magnitude of said power is defined by the power P_{in} corresponding to a current supplied during the period T_{on} (t_0 to t_1), that is, the power supplied from the power source 4, and a return power P_{ret} indicated by a current brought back to the power source 4. Therefore, the net power P_{out} supplied from the power source 4 to the load 10 is expressed as follows:

$$P_{out} = P_{in} - P_{ret}.$$

Now let it be assumed that a current i_L returned to the power source 4 during a period T_d (t_2 to t_3) is regarded as a current i_c flowing back through the GTO thyristor 5. Then, the above-mentioned net transmitted power may be expressed by the following equation:

$$\begin{aligned}
 P_{out} &= \frac{1}{T} \int_0^{T_{on}} \{i_c(t) \cdot E_{in}\} dt \\
 &= \frac{1}{2T} \left\{ \frac{E_{in}^2 (T_{on}^2 - T_d^2)}{L_p} \right. \\
 &\quad \left. + \frac{nE_{out}(E_{in} - nE_{out})}{L_e} (T_{on} + T_d)^2 \right\} .
 \end{aligned}$$

As seen from the above equation, it is very effective to reduce the value L_p of the exciting inductance 13 and the value L_e of the leakage inductance 14 for the object of increasing the transmitted power. In this connection, it will be noted that the above-mentioned inductance values L_p , L_e primarily depend on the winding construction of the transformer 1.

A high voltage-generator embodying this invention offers the advantages that the application of the coreless transformer 1 enables not only the size of the transformer 1, and consequently the whole high voltage generator, but also the inductance values L_p , L_e to be reduced, ensuring the effective transmission of a large power. Said coreless transformer 1 is also improved in responsibility, broadening the response frequency band and facilitating the insulation of high voltage; consequently, it is possible to eliminate the so-called coreloss of the transformer 1 and resolve various problems arising from, for example, magnetic saturation. Moreover, the high frequency switching operation and the miniaturization of the high voltage generator can be promoted. The application of a coreless transformer generally tends to be accompanied with the drawback that a magnetic connection between the primary and secondary windings tends to be more weakened than when a core transformer is used. As described above, however, the coreless transformer 1 of the subject high voltage generator is constructed by dividing the secondary winding 3 into three sections. In this case, the divided sections of the secondary

winding 3 of the coreless transformer 1 are wound about the outer periphery and/or the inner periphery of the primary winding 2. A good electromagnetic bonding is realized between both primary and secondary windings 2, 3. Since the transformer is operated with a high frequency, which is adapted to provide a strong electromagnetic bonding, even the application of the coreless transformer 1 gives rise to substantially no decline in the electromagnetic bonding.

The present inventors manufactured four samples of the coreless transformer 1 whose L_p values, respectively indicated 20 μH , 40 μH , 80 μH and 160 μH under the condition of $L_e = 0.5 L_p$. A test was made of the high voltage generators embodying this invention, which respectively involved said four samples of the coreless transformer 1. Determination was made of the relationship between the operation frequency f and the quantity P_{out} of a supplied power which was observed under the condition of:

$$\begin{aligned} E_{\text{in}} &= 500 \text{ V,} \\ E_{\text{out}} &= 150 \text{ KV,} \\ n &= 1/500, \\ T_{\text{on}}/T &= 0.4, \\ T_{\text{d}}/T &= 0. \end{aligned}$$

As a result, the relationship indicated in Fig. 5 was obtained. Fig. 5 proves that when a transformer 1 in which $L_p = 160 \mu\text{H}$ results, is applied to produce a power P_{out} of for example, 300 KW, it is advised to set the operation frequency at 0.96 KHz. In the case of a transformer of $L_p = 80 \mu\text{H}$, the operation frequency should advisably be set at 1.82 KHz. In the case of a transformer of $L_p = 40 \mu\text{H}$, the operation frequency should advisably be set at 3.56 KHz. Finally, in the case of a transformer of $L_p = 20 \mu\text{H}$, the operation frequency should preferably be set at 7.4 KHz. The result of the above-mentioned

determination means that if the subject high voltage generator is provided with a coreless transformer 1 which enables the L_p of the exciting inductance 13 to be set at 20 to 30 μH , said generator can be operated at a higher frequency than, for example, 5 KHz even when power as large as 100 KW is transmitted. In other words, when a power of hundreds of kilowatts is transmitted with the high voltage generator operated at a high frequency of several KHz units, it is necessary to apply a transformer 1 of $L_p = 20$ to 30 μH . The high voltage generator of this invention, which involves the aforementioned coreless transformer, can attain the above-mentioned object.

As compared with the inductance of an air core (coreless) coil, the conventional transformer, which involves a core consisting of laminated silicon steel plates and in which the core magnetic permeability is larger than 1, indicates a larger inductance. When 30 turns of a wire are wound about a bobbin having a diameter of, for example, 60 mm, a coreless coil has an inductance as large as 40 μH . When, therefore, such a coil involves a core prepared from the above-mentioned laminated silicon steel plates, the resultant inductance is greatly increased. The above-mentioned coreless coil has a magnetic flux density expressed as:

$$B = \frac{100 \times 10 \times 500^V}{(\pi \times 3^2) \times 30^T} \times 10^8$$

$$= 1.768 \times 10^5 \text{ (gausses) (17,68T)}$$

Therefore, a coil involving the aforementioned core prepared from laminated silicon steel plates indicates a magnetic flux density of 1,8T (18,000G), if manufactured under the same conditions as a coreless coil except for the presence of said silicon steel plate

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coil. The above-mentioned magnetic flux density of 1,8T (18,000G) is 10 times higher than that which is observed in a coreless coil.

5 As mentioned above, a high voltage generator embodying this invention, which involves a coreless transformer 1, offers the advantages that the transformer 1 can be miniaturized, and the generator can be operated at a high frequency, ensuring the effective transmission of a large volume of power.

10 The operation frequency of the subject high voltage generator, the inductance of the transformer 1 and the ratio which the turns of the primary winding of said transformer 1 bear to those of the secondary winding thereof are determined in accordance with the required specification. The power supply to a load can be controlled by varying either the period of a control pulse issued from the control pulse generator 6

15 to the GTO thyristor 5 or the pulse width (the timing in which the GTO thyristor 5 is intermittently rendered conducting), or both factors. Obviously, the high voltage generator embodying this invention which is constructed as described above is applicable as a power source for any other load than the X-ray tube 10.

20 The switch element of the subject high voltage generator can be provided not only by the aforementioned GTO thyristor 5, but also by the so-called giant transistor, thyristor or any other electronic switch element having the same control function as the aforementioned elements. When, however, an electronic switch element, for example, a thyristor having no

25 self-extinguishing function, is applied, it is of course necessary to provide an extinguishing circuit interlockingly operative with the control pulse generator 6 for the purpose of effecting extinction.

30

35 A second embodiment of this invention shown in Fig. 6 comprises a voltage resonance circuit constructed by connecting a resonance capacitor 21 in parallel to

the primary winding of the transformer 1. The arrangement of Fig. 6 is substantially equivalent to that of Fig. 1 with respect to a high frequency. A description may now be made, with reference to

5 Fig. 7, of a high voltage generator according to a third embodiment of this invention. A thyristor 22 acting as an auxiliary switching element is connected in series to the resonance capacitor 7 between the

10 primary winding 2 of the transformer 1 and said resonance capacitor 7 shown in Fig. 1. A control pulse generator 23 causes the GTO thyristor 5 acting as a main switch to be intermittently operated for a prescribed period in a prescribed time, thereby enabling the operating time of said thyristor 22

15 to be controlled as desired, thus ensuring the control of the power magnitude supplied to a load, for example, the X-ray tube 10. The thyristor 22 acting as an auxiliary switching element controls the recharge of the resonance capacitor 7 during the

20 resonance mode, thereby ensuring the control of an output power over a broad range.

Claims:

1. A high voltage generator being characterized in that said generator comprises:
- a coreless transformer (1) provided with a primary winding (2) and a secondary winding (3);
 - 5 switching means (5) connected in series between the primary winding of the transformer (1) and a D.C. source (4);
 - switch-driving means (6) connected to the switching means (5) to periodically control the conductive and
 - 10 nonconductive conditions of said switching means;
 - voltage resonance capacitors (7, 21) connected in parallel to said switching means (5) or the primary winding (2) of said transformer (1); and
 - a rectifier circuit (9) connected to the secondary
 - 15 winding (3) of said transformer (1) to rectify an output current from said secondary winding (3) for supplying a load (10).
2. A high voltage generator according to claim 1, which is characterized in that said switch-driving means
- 20 is a pulse-generating means (6) for supplying a high frequency pulse to the switching means (5).
3. A high voltage generator according to claim 1, which is characterized in that the secondary winding of the transformer (1) connected to said rectifier circuit is
- 25 composed of a plurality of divided windings (3).
4. A high voltage generator according to claim 3, which is characterized in that the rectifier circuit comprises a plurality of groups of diodes (9) connected in series to each other, every two diode groups are
- 30 connected in parallel, and each of the divided windings (3) is connected between a junction of every two adjacent diodes constituting one group and a junction of every two corresponding adjacent diodes constituting another adjacent group.
- 35 5. A high voltage generator according to any of claims

which is characterized in that second switching means (22) is connected between the switching means (5) and the primary winding (2) of the transformer (1) in series to said switching means (5), second switch-driving
5 means (23) is provided to control the conductive and nonconductive conditions of said second switching means (22), and said second switch-driving means (23) controls the conductive and nonconductive conditions
10 of said second switching means (22) in a variable timing.

6. A high voltage generator according to claim 1, which is characterized in that said switching means is formed of a semiconductor switching element (5) acting as a diode.

15 7. A high voltage generator according to claim 6, which is characterized in that a by-pass diode (8) is connected in inverse parallel to said semiconductor switching element (5).

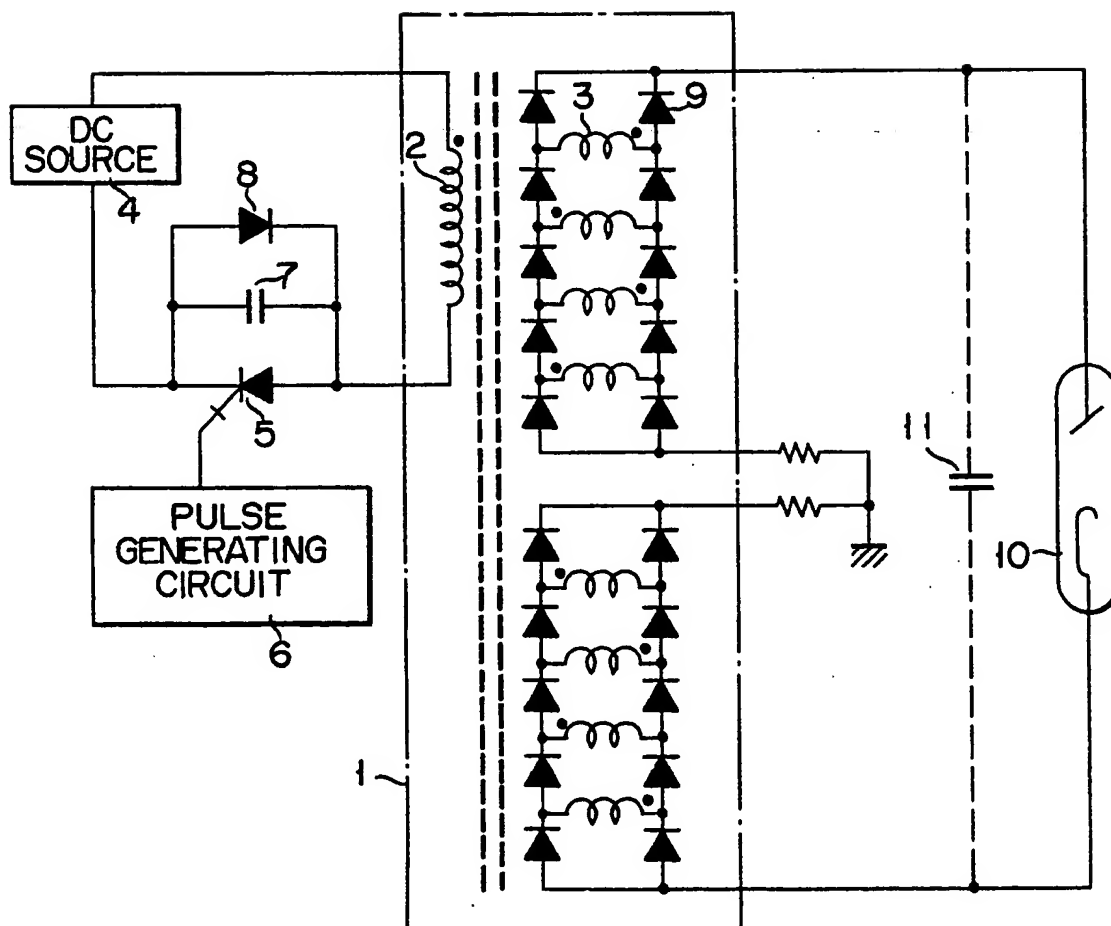
20 8. A high voltage generator according to claim 6, which is characterized in that said semiconductor switching element is a gate turn-off thyristor (5).

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FIG. 1



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FIG. 2

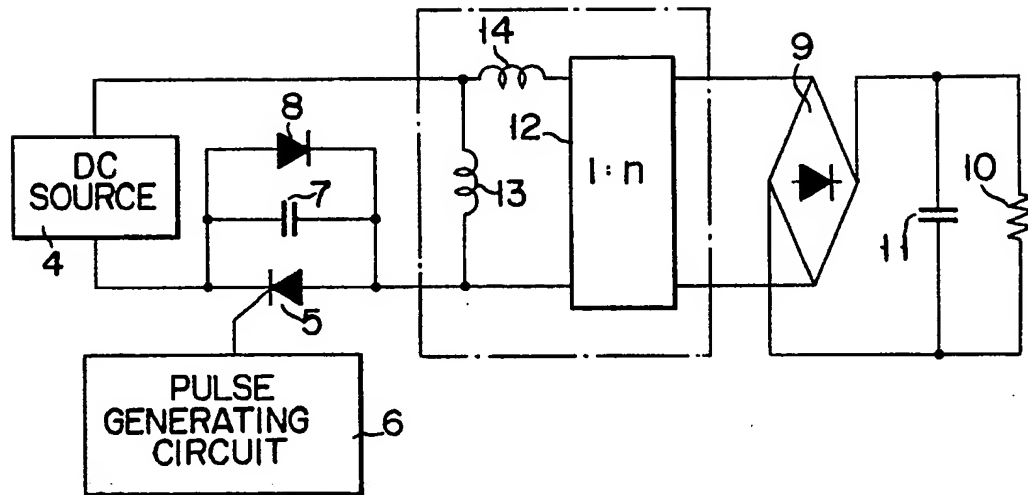


FIG. 3A

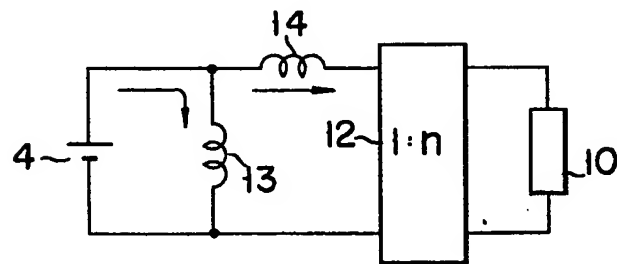


FIG. 3B

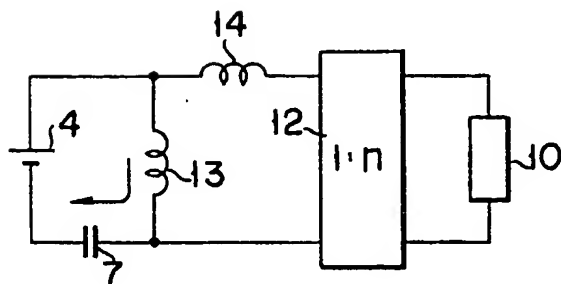


FIG. 3C

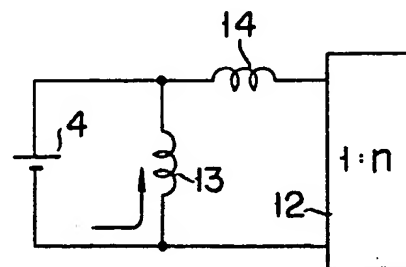
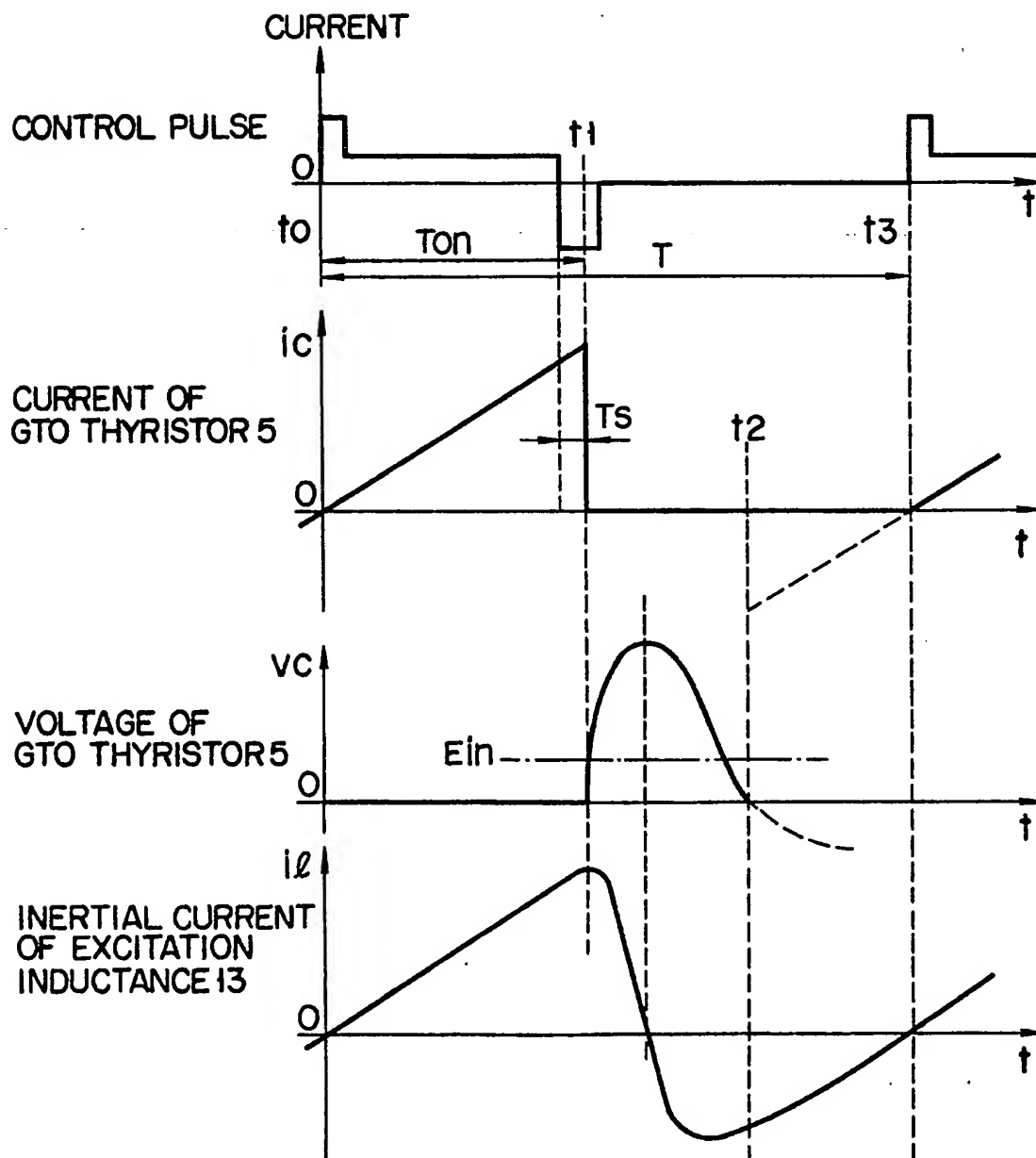


FIG. 4



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FIG. 5

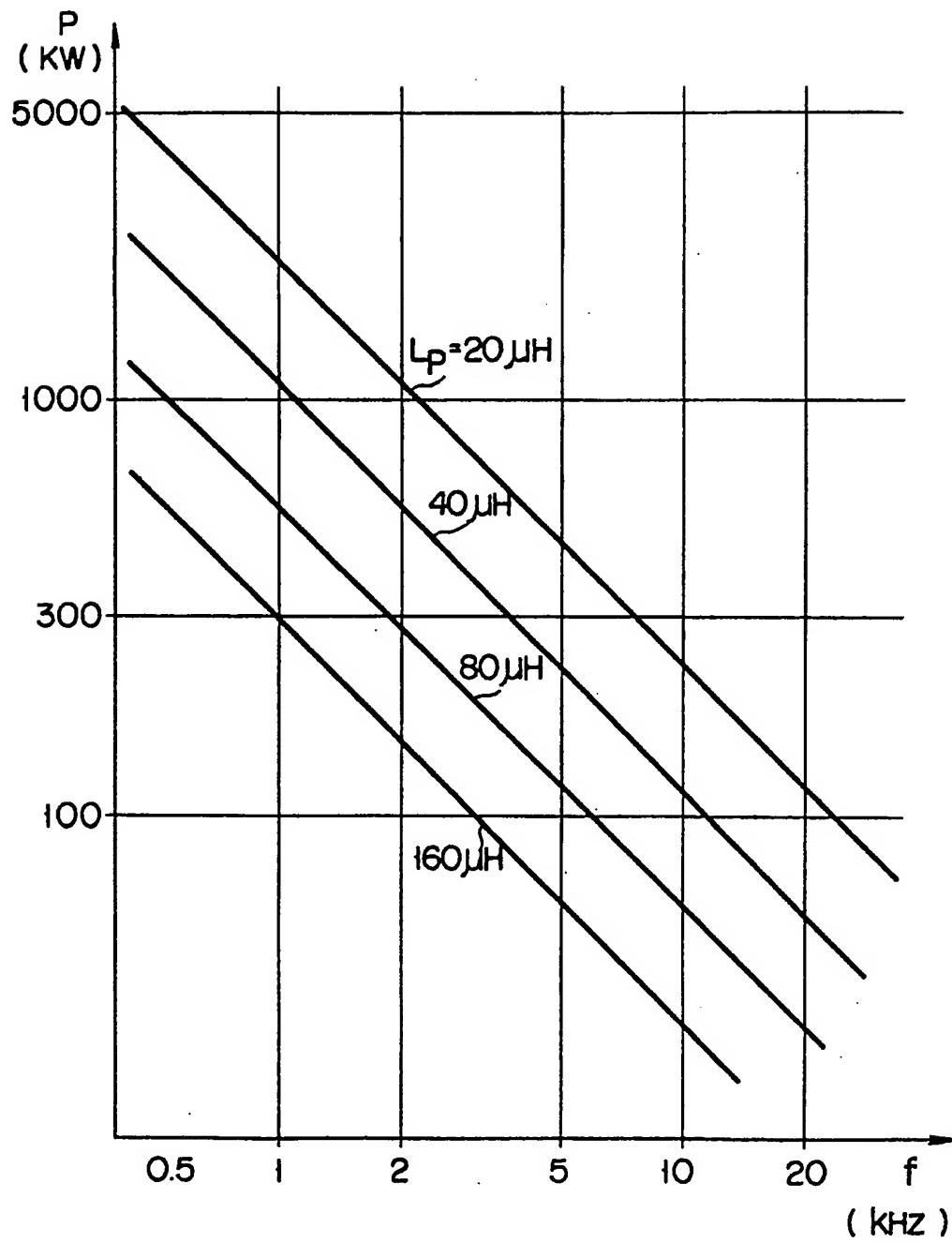
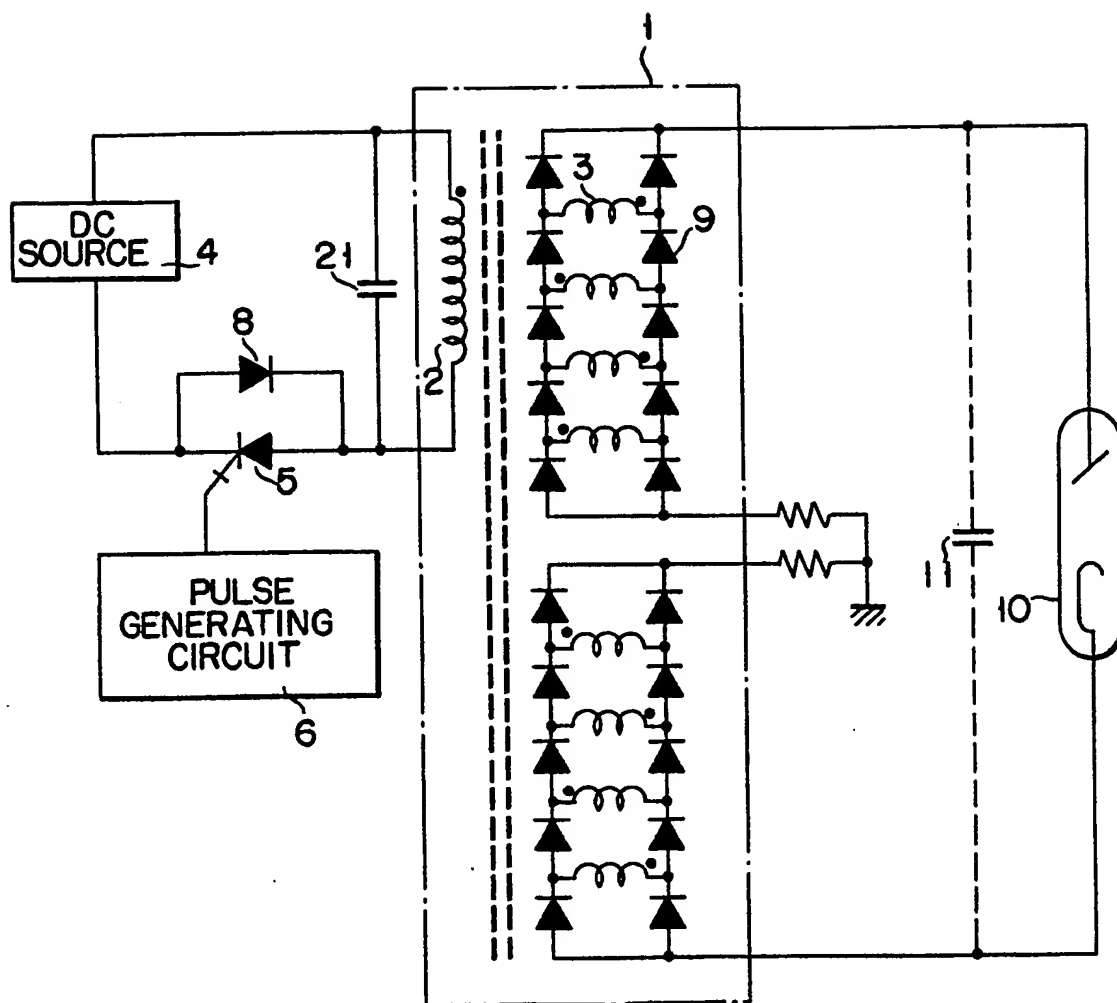
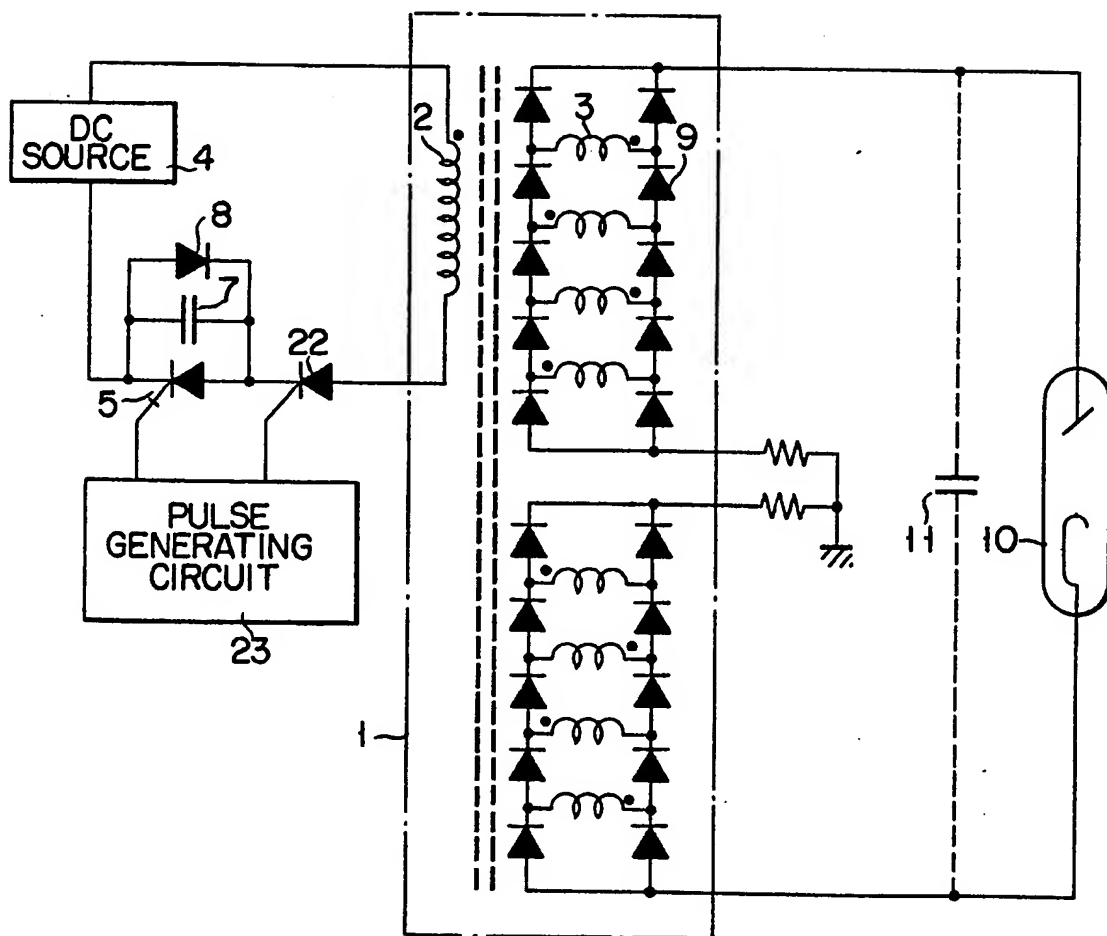


FIG. 6



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FIG. 7





European Patent
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EUROPEAN SEARCH REPORT

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Application number

EP 84 11 1492

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
X	EP-A-0 106 482 (TOKYO SHIBAURA DENKI) * page 4, line 27 - page 6, line 13 *	1, 3, 4, 7	H 02 M 3/28 H 05 G 1/24
A	EP-A-0 058 399 (TOKYO SHIBAURA DENKI) * page 3, lines 4-34 * -----	1, 7	
			TECHNICAL FIELDS SEARCHED (Int. Cl.4)
			H 02 M H 05 G
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 10-12-1984	Examiner KERN H.
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